

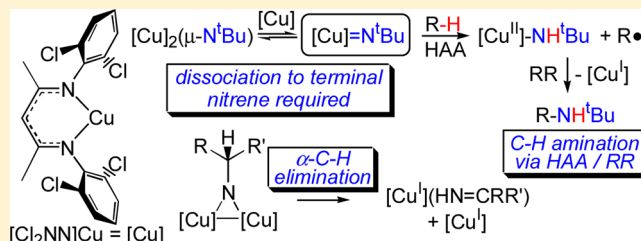
Mechanistic Insights into C–H Amination via Dicopper Nitrenes

Mae Joanne B. Aguila, Yosra M. Badiei, and Timothy H. Warren*

Department of Chemistry, Georgetown University, Box 571227-1227, Washington, D.C. 20057, United States

S Supporting Information

ABSTRACT: We examine important reactivity pathways relevant to stoichiometric and catalytic C–H amination via isolable β -diketiminato dicopper alkylnitrene intermediates $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-NR})$. Kinetic studies involving the stoichiometric amination of ethylbenzene by $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-N}^t\text{Bu})$ (**3**) demonstrate that the terminal nitrene $[\text{Cl}_2\text{NN}]\text{Cu}=\text{N}^t\text{Bu}$ is the active intermediate in C–H amination. Initial rates exhibit saturation behavior at high ethylbenzene loadings and an inverse dependence on the copper species $[\text{Cl}_2\text{NN}]\text{Cu}$, both consistent with dissociation of a $[\text{Cl}_2\text{NN}]\text{Cu}$ fragment from **3** prior to C–H amination. C–H amination experiments employing 1,4-dimethylcyclohexane and benzylic radical clock substrate support a stepwise H-atom abstraction/radical rebound pathway. Dicopper nitrenes $[\text{Cu}]_2(\mu\text{-NCHRR}')$ derived from 1° and 2° alkylazides are unstable toward tautomerization to copper(I) imine complexes $[\text{Cu}](\text{HN}=\text{CRR}')$, rendering 1° and 2° alkylnitrene complexes unsuitable for C–H amination.

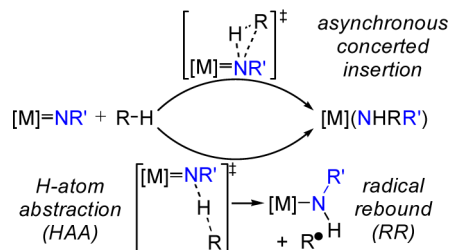


INTRODUCTION

Catalytic C–H amination represents an appealing approach for preparation of nitrogen containing compounds without requiring typical functional group manipulations.¹ A majority of these protocols are proposed to proceed through metal-nitrene species $[\text{M}]=\text{NR}'^2$ which may directly react with a C–H bond in substrates R–H to give amines R–NHR'. Commonly, isolable or in situ prepared nitrene precursors such as iminoiodinanes $\text{PhI}=\text{NR}$ based on electron-deficient sulfonylamines $\text{H}_2\text{NSO}_2\text{R}$ or carbamates $\text{H}_2\text{NC}(\text{O})\text{OR}$ have been used with dirhodium^{3,4} or ruthenium catalysts.^{5–7} Nonetheless, the quest for more earth abundant, economical C–H functionalization catalysts motivates the investigation of first-row transition metal systems based on Mn,⁸ Fe,^{9,10} Co,^{11,12} and Cu.^{13–16}

Only in a few cases, however, may discrete metal-nitrene species be isolated and subjected to detailed analysis. Che isolated and kinetically studied the novel (porph)Ru(=NSO₂R')₂ featuring *trans*-[M]=NSO₂R' moieties.⁵ Based on the primary KIEs of 4–11 observed in reactions with benzylic C–H bonds in substrates R–H, these reactions were suggested to proceed via H-atom abstraction (HAA)/radical recombination (RR) pathways to give the C–H amination products RNH(SO₂R'). Cenini crystallographically characterized the related electron-poor derivative (porph)Ru(=NAr^F)₂ (Ar^F = 3,5-(CF₃)₂C₆H₃).¹⁷ Isolation of the bis(amide) (porph)Ru(N-(1-cyclohexenyl)Ar^F)₂ derived from the addition of 2 equiv of the cyclohexenyl radical to (porph)Ru(=NAr^F)₂ in the C–H amination of cyclohexene suggested a similar HAA/RR mechanism. These stepwise C–H amination pathways should be contrasted with an asynchronous concerted mechanism identified using stereochemical probes via putative $[\text{Rh}_2]=\text{NT}$ species (Scheme 1).³

Scheme 1. C–H Amination via Metal–Nitrenes



Previously we described the isolation of dicopper nitrenes $[\text{Cu}]_2(\mu\text{-NR})$ (R = aryl, Ad) obtained from the reaction of copper(I) β -diketiminates with organoazides N₃R.^{15,18} For instance, the dicopper nitrene $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-NAd})$ (**1**) ($[\text{Cl}_2\text{NN}] = 2,4\text{-bis}(2,6\text{-dichloro})\text{phenylimido}p\text{entyl}$) may be isolated from the reaction of $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-benzene})$ (**2**) with the organoazide N₃Ad (Ad = 1-adamantyl). This species formally inserts the NAd group into *sp*³-hybridized C–H bonds under stoichiometric and catalytic conditions (Scheme 2).¹⁵ Furthermore, this is the first example of an isolated copper nitrene species that participates in intermolecular nitrene transfer to C–H substrates.

Despite considerable interest, no terminal copper nitrene complex has been isolated to allow for clear mechanistic studies.¹⁶ The dicopper nitrenes $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-NAd})$, $\{[\text{Me}_3\text{NN}]\text{Cu}\}_2(\mu\text{-NAd})$, and $\{[\text{Me}_3\text{NN}]\text{Cu}\}_2(\mu\text{-NAr})$ (Ar = 3,5-Me₂C₆H₃) represent the only species characterized by X-ray (Figure 1). Solution studies suggested the possibility of dissociation of a β -diketiminato copper(I) fragment from $[\text{Cu}]_2(\mu\text{-NAr})$ (Figure 1) during the formation of an

Received: January 25, 2013

Scheme 2. Copper Nitrene-Based C–H Amination

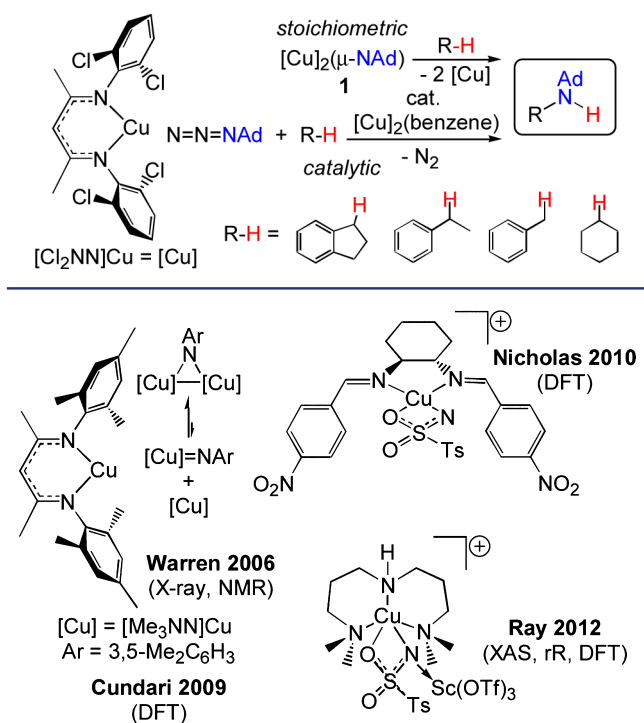


Figure 1. Previously investigated copper nitrenes.

unsymmetrical species $[\text{Cu}](\mu\text{-NAr})[\text{Cu}']$ in the presence of an additional β -diketiminato-like species $[\text{Cu}']$.¹⁸

Since the first observation of C–H amination and alkene aziridination with sulfonyl azides in the presence of copper,¹⁹ copper sulfonylnitrene species have attracted significant interest (Figure 1).¹⁶ Calculations on Nicholas's cationic bis(imine) copper system showed that $\kappa^2\text{-N,O-NTs}$ copper species represent the most likely intermediates for the C–H amination.²⁰ The close separation of calculated triplet (ground) and multiconfigurational singlet (excited) states leads to a bifurcation of reaction pathways: the former is predicted to react through stepwise HAA/RR, while the latter should react in a concerted fashion. Quite recently, Lewis acid adducts of a cationic copper-tosylnitrene supported by tridentate amine isolated at low temperature have been reported.²¹ Substantiated by XAS and resonance Raman studies, DFT studies point to a $\kappa^2\text{-N,O-NTs}$ binding mode in which the nitrene N-donor engages a Lewis acid such as $\text{Sc}(\text{OTf})_3$. Reactivity studies reveal that this species aminates sp^3 C–H bonds in substrates such as toluene and even cyclohexane in modest yields (21–35%).

Direct, asynchronous, insertion of a metal-nitrene into a C–H bond and H-atom/radical rebound (HAA/RR) represent two opposing pathways considered for C–H functionalization with metal nitrenes (Scheme 1). While putative $[\text{Rh}]_2=\text{NSO}_2\text{R}$ intermediates have been probed with radical clock substrates to give evidence for a concerted pathway,³ related copper-based systems employing diimine ligands provide evidence for contributions from both pathways.²⁰ Moreover, the identification of an HAA/RR pathway for β -diketiminato $[\text{Cu}]=\text{NR}'$ species would specifically implicate three-coordinate copper(II) amides $[\text{Cu}^{\text{II}}\text{-NHR}']$ as active intermediates. Recent synthetic and kinetic studies have revealed such $[\text{Cu}^{\text{II}}\text{-NHR}']$ species to be active in stoichiometric C–H functionalization themselves, capable of both HAA of benzylic substrates

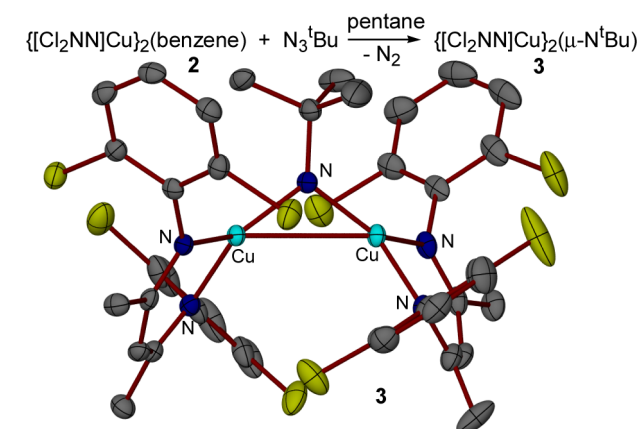
R–H as well as capture of the resulting radical R^\bullet to give the functionalized amines $\text{R-NHR}'$.²²

Herein we report mechanistic investigations into stoichiometric and catalytic C–H amination via dicopper nitrenes that points to the importance of dissociation of a β -diketiminato fragment $[\text{Cu}^{\text{I}}]$ from $[\text{Cu}]_2(\mu\text{-NR}')$ species to generate terminal nitrenes $[\text{Cu}]=\text{NR}'$ that directly react with C–H substrates R–H. Use of stereochemical probes provides insight into the nature of the C–H \rightarrow C–N transformation. Examination of reactions with 1° and 2° alkyl azides $\text{N}_3\text{CHRR}'$ (R, R' = H or alkyl) reveal that dicopper nitrenes $[\text{Cu}]_2(\mu\text{-NCHRR}')$ may be isolated, but rapidly convert to $[\text{Cu}^{\text{I}}](\text{NH}=\text{CRR}')$ species in arene solvents where dissociation of a β -diketiminato copper(I) fragment $[\text{Cu}^{\text{I}}]$ is favored.

RESULTS AND DISCUSSION

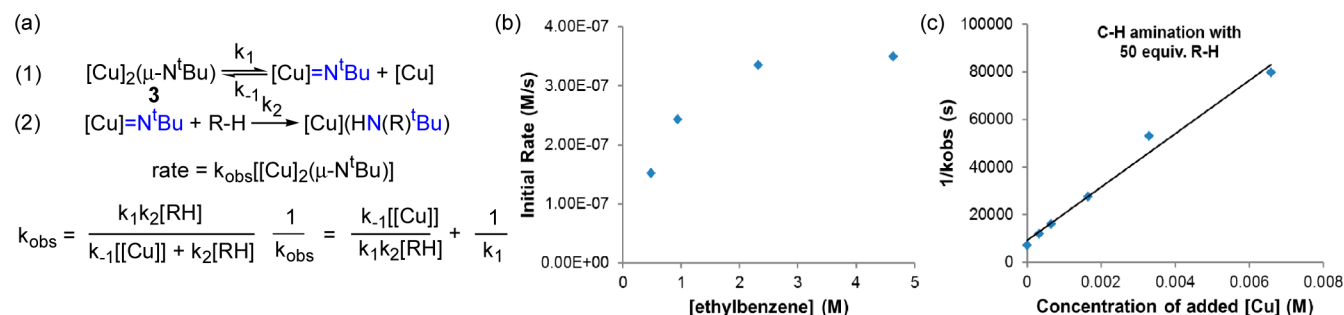
Synthesis and Characterization of $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-N}^t\text{Bu})$ (3). Stirring the copper(I) precursor $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-benzene})$ ¹⁵ (2) with the 3° organoazide N_3^tBu in pentane gives $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-N}^t\text{Bu})$ (3) as green crystals in 46% yield (Scheme 3). The X-ray structure of 3 shows a bridging nitrene

Scheme 3. Synthesis and X-ray Structure of Dicopper Nitrene 3



unit similar in form to the *N*-adamantyl variant 1.¹⁵ The nearly C_2 -symmetric *tert*-butylnitrene complex 3 exhibits $\text{Cu-N}_{\text{nitrene}}$ distances of 1.808(3) and 1.815(3) Å nearly identical to those in 1 (1.810(2) Å). The $\text{Cu}\cdots\text{Cu}$ separation of 2.9147(6) Å in 3 is somewhat shorter than that found in 1 (2.969(1) Å) likely due to the slightly smaller steric impact of the ^tBu group compared to Ad. ^1H and $^{13}\text{C}\{^1\text{H}\}$ NMR spectra of 3 reveal only one type each of *N*-aryl *p*-H and *m*-H environments, even down to -70°C in toluene- d_6 , indicating facile rotation about the $\text{Cu-N}_{\text{nitrene}}$ bonds at the expense of any $\text{Cu}\cdots\text{Cu}$ interaction (Supporting Information Figures S9–S10 and Scheme S7).

Kinetic Investigation of $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$ Reactivity with Ethylbenzene. We performed a series of kinetics experiments that support the dissociation of a $[\text{Cl}_2\text{NN}]\text{Cu}$ fragment ($[\text{Cu}^{\text{I}}]$) from 3 to generate the terminal nitrene $[\text{Cl}_2\text{NN}]\text{Cu}=\text{N}^t\text{Bu}$ ($[\text{Cu}]=\text{N}^t\text{Bu}$) responsible for C–H amination reactivity (Scheme 4a). The progress of the stoichiometric reaction of 3 ($[\text{3}]_0 \sim 0.5$ mM) and varying equivalents of ethylbenzene was monitored through loss of the intense optical band of the dicopper nitrene 3 ($[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$) at $\lambda_{\text{max}} = 714$ nm ($\epsilon = 3960$ $\text{M}^{-1}\text{cm}^{-1}$) using the method of initial rates (Supporting Information Figure S2). The initial rate of decay of $[\text{Cu}]_2(\mu\text{-$

Scheme 4. Kinetic Analysis of Stoichiometric C–H Amination of Ethylbenzene (R–H) by **3** at 40 °C in Benzene

N^tBu) (**3**) in benzene at 40 °C increases with added ethylbenzene (1000–10000 equiv), but exhibits saturation at higher ethylbenzene concentrations (Scheme 4b). This behavior is inconsistent with direct reaction between the dicopper nitrene $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$ (**3**) and ethylbenzene. This also indicates a pre-equilibrium step involving dissociation of $[\text{Cu}]$ from $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$ (**3**) to form the terminal nitrene $[\text{Cu}]=\text{N}^t\text{Bu}$ prior to the irreversible C–H functionalization step (Scheme 4a).

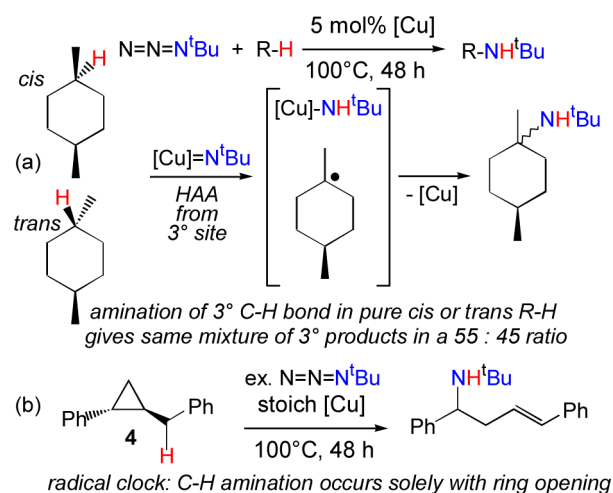
To more closely monitor the dissociation of $[\text{Cu}]$ from $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$ (**3**) that enables C–H amination by $[\text{Cu}]=\text{N}^t\text{Bu}$, we followed the stoichiometric reaction of $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$ (**3**) with ethylbenzene in the presence of varying concentrations of added $[\text{Cu}]$. An inverse dependence of the rate on both the concentration of $[\text{Cu}]$ and R–H is expected from the rate law derived from steady-state approximation of a mechanistic scenario that involves dissociation of $[\text{Cu}]$ from $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$ (k_1/k_{-1}) to give low concentrations of $[\text{Cu}]=\text{N}^t\text{Bu}$ that participates in C–H amination (k_2) (Scheme 4a and Supporting Information Scheme S1). Careful control of the concentration of ethylbenzene is essential to observe a clear dependence of the initial rate on added $[\text{Cu}]$. Employing an ethylbenzene concentration of 16.5 mM (50 equiv/**3**), kinetic analysis at 40 °C reveals an inverse dependence of initial rate of loss of **3** on the concentration of added $[\text{Cu}]$ (0–20 equiv/**3**). A plot of $1/k_{\text{obs}}$ versus the concentration of added $[\text{Cu}]$ is linear whose y -intercept is the inverse of the rate constant $k_1 = 1.1(3) \times 10^{-4} \text{ s}^{-1}$ for dissociation of $[\text{Cu}]$ from $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$ (**3**) under these conditions (Scheme 4c).

Stereochemical Probes: Mechanism of C–H Functionalization. We then turned our attention to the mechanism by which $[\text{Cl}_2\text{NN}]\text{Cu}=\text{N}^t\text{Bu}$ formally inserts the N^tBu moiety into C–H bonds. Concerted (likely asynchronous) and stepwise (HAA/RR) pathways represent two limiting mechanistic scenarios by which C–H substrates R–H could react with the key $[\text{Cl}_2\text{NN}]\text{Cu}=\text{N}^t\text{Bu}$ intermediate to give $\text{R-NH}^t\text{Bu}$. We employed two different types of mechanistic probes R–H that each support a stepwise HAA/RR pathway by providing evidence for the intermediacy of the corresponding radical R^\bullet in the C–H amination of R–H by **3**.

Reaction of *cis*- and *trans*-1,4-dimethylcyclohexane (20 equiv) with N_3^tBu catalyzed by 5 mol % $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\text{benzene})$ (**2**) at 100 °C leads to the C–H amination of 3° and 2° C–H bonds in these substrates in combined yields of 58% and 50% for the *cis*- and *trans*-isomers, respectively (Supporting Information Scheme S3). Importantly, amination of the 3° C–H bond in either the *cis*- or *trans*-isomer leads to the *same two* products in essentially equal ratios (46:54 and 44:56, respectively). These findings clearly indicate the intermediacy of a 3° radical R^\bullet that leads to a diastereomeric

mixture of 3° C–H amination products $\text{R-NH}^t\text{Bu}$ (Scheme 5a). We also found that the amount of secondary inserted products

Scheme 5. Catalytic C–H Amination of Mechanistic Probes



depends on the relative accessibility of the distinct 2° C–H bonds in the *cis* and *trans* isomers. The *cis* isomer gave only one product, while the *trans*-isomer gave two products (Supporting Information Scheme S4). Functionalization of the 3° C–H bond in the *cis*-substrate is more favorable than in the *trans*-substrate, giving a 3°:2° C–H amination product distribution of 75:25 and 25:75, respectively. This may be the result of greater steric interactions between the axial 4-methyl group in the *trans*-substrate and the $[\text{Cl}_2\text{NN}]\text{Cu}=\text{N}^t\text{Bu}$ intermediate as it approaches the somewhat weaker tertiary C–H bond (Supporting Information Scheme S5).

Use of a benzylic radical clock further supports a stepwise mechanism for C–H amination (Scheme 5b). HAA from the benzylic position of 1-benzyl-*trans*-2-phenylcyclopropane (**4**) results in a radical that quickly rearranges ($k = 3.6(5) \times 10^8 \text{ s}^{-1}$)²³ to its ring-opened form. C–H amination of radical clock **4** (1 equiv) with excess N_3^tBu at 100 °C employing a full equivalent of $[\text{Cu}]$ gives only one product, the ring-opened product in 80% yield. ¹H NMR analysis of the HCl-salt of this product clearly shows the *trans*-configuration of the resulting C=C bond in the ring opened product (J_{HH} for vinylic H = 16 Hz).

Formation of Copper Imine Complexes from New Dicopper Alkylnitrenes. In our examination of the range of alkylazides that may participate in C–H amination using our catalytic protocols, we used representative 1° and 2° organoazides N_3R to probe the possibility of new isolable dicopper 1°

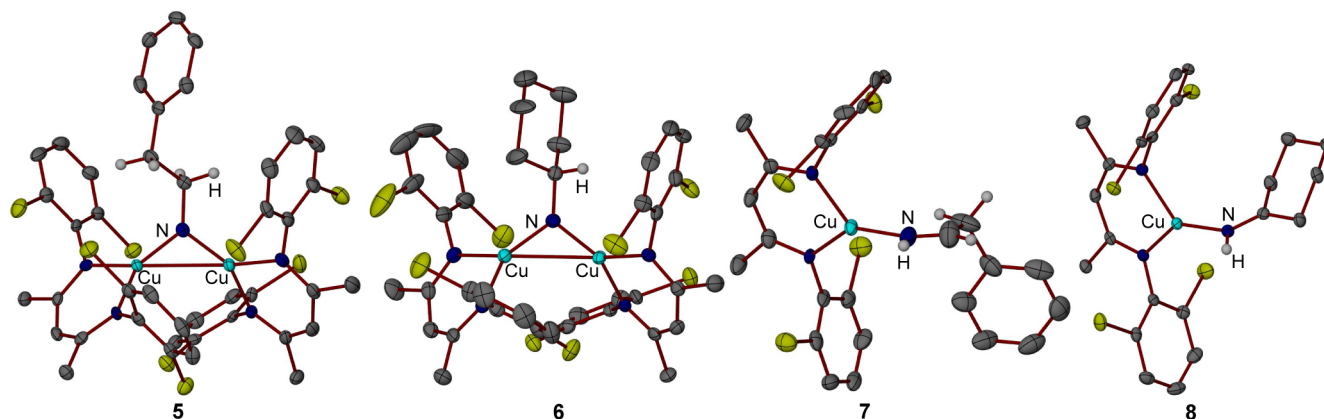
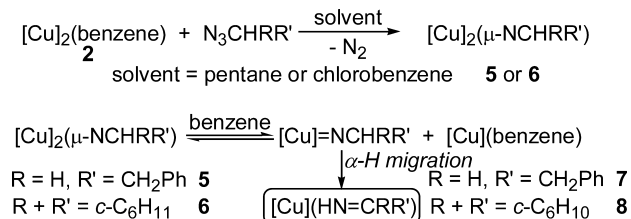


Figure 2. X-ray structures of dicopper alkylnitrenes $[\text{Cu}]_2(\mu\text{-NCHRR}')$ **5** and **6** and imine adducts $[\text{Cu}](\text{HN}=\text{CRR}')$ **7** and **8**.

and 2° alkylnitrene species. Addition of $\text{N}_3\text{CH}_2\text{CH}_2\text{Ph}$ or N_3Cy to **2** in chlorobenzene or pentane results in immediate coloration of the chlorobenzene or pentane solution (Scheme 6). Dark purple crystals of $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-NCH}_2\text{CH}_2\text{Ph})$ (**5**) and dark blue green crystals of $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-N}(c\text{-C}_6\text{H}_{11}))$ (**6**) may be isolated suitable for X-ray diffraction by low temperature crystallization from pentane immediately following their synthesis (Figure 2). The $\text{Cu}-\text{N}_{\text{nitrene}}$ distances in **5** (1.782(3) and 1.793(3) Å) and **6** (1.793(3) and 1.804(3) Å) are similar to those in **1** and **3**. These $\text{Cu}-\text{N}$ distances are shorter than the $\text{Cu}-\text{N}_{\text{amide}}$ distance of 1.839(9) Å in the copper(II) amide compound $[\text{Cl}_2\text{NN}]\text{Cu-NHAd}$.²² The $\text{Cu}\cdots\text{Cu}$ contacts of 2.8673(6) and 2.8782(7) Å in **5** and **6**, however, are further contracted than those found in **1** and **3** due to the lower steric demand of the smaller N -alkyl substituents. This is also results in a less obtuse $\text{Cu}-\text{N}_{\text{nitrene}}-\text{Cu}$ angle of 106.65(16)° for **5** and 106.30(17)° for **6** as compared to 107.09(13)° for **3**.

We found that these 1° and 2° alkylnitrene complexes **5** and **6** are more significantly thermally sensitive than **1** and **3**. Rather than participating in C–H amination of substrates such as ethylbenzene, dissolution of either **5** or **6** in benzene at RT results in the rapid conversion to the copper(I) imine adducts $[\text{Cl}_2\text{NN}]\text{Cu}(\text{HN}=\text{CHCH}_2\text{Ph})$ (**7**) or $[\text{Cl}_2\text{NN}]\text{Cu}(\text{HN}=\text{C}(c\text{-C}_6\text{H}_{10}))$ (**8**) along with release of $[\text{Cl}_2\text{NN}]\text{Cu}$ (Scheme 6). $\alpha\text{-H}$

Scheme 6. Facile Nitrene to Imine Transformation



migration qualitatively takes place much more quickly in benzene than in solvents that do not coordinate well to the $[\text{Cl}_2\text{NN}]\text{Cu}$ fragment such as ether or pentane. Thus, loss of $[\text{Cl}_2\text{NN}]\text{Cu}$ from **5** and **6** to form the corresponding terminal 1° and 2° alkylnitrene complexes $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NCHRR}'$ likely precedes $\alpha\text{-H}$ migration to give the imine adducts **7** and **8**. Consistent with the rapid conversion of $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NCHRR}'$ intermediates to the corresponding imines $[\text{Cl}_2\text{NN}]\text{Cu}(\text{HN}=\text{CRR}')$, attempted C–H amination of ethylbenzene with either **5** or **6** did not provide any C–H functionalized

product nor did attempted catalytic C–H amination of ethylbenzene with $\text{N}_3\text{CH}_2\text{CH}_2\text{Ph}$ or N_3Cy in the presence of **2**. While the ethylbenzene C–H amination product with N_3^tBu does not bind to the $[\text{Cu}]$ catalyst in benzene- d_6 , the imine products $\text{HN}=\text{CRR}'$ in **7** and **8** do bind to the $[\text{Cu}]$ catalyst in benzene- d_6 , indicating that these imines could inhibit efficient catalytic transformations of the corresponding azides $\text{N}_3\text{CHRR}'$.

The X-ray structures of **7** and **8** (Figure 2) reveal trigonal coordination at Cu with $\text{Cu}-\text{N}_{\text{imine}}$ distances of 1.885(5) and 1.914(2) Å. These compounds have short $\text{C}=\text{N}_{\text{imine}}$ distances of 1.223(8) and 1.275(3) Å, respectively, compared to the $\text{C}-\text{N}_{\text{nitrene}}$ distances of **5** and **6** (1.434(4) and 1.435(5) Å, respectively). The aldimine N–H moieties give rise to high energy bands at 3283 and 3276 cm^{-1} in the IR spectra of **7** and **8**.

DISCUSSION AND CONCLUSIONS

Terminal copper nitrenes have long been considered as reactive intermediates in the nitrene group transfer reactions of alkene aziridination and C–H amination. Due to their high anticipated reactivity illustrated by reaction with unactivated 2° and 3° C–H bonds, challenges still remain in the isolation of these species. Nonetheless, a “protected” form of the terminal nitrene allows for the isolation of dicopper nitrenes $[\text{Cu}]_2(\mu\text{-NR})$ that may dissociate a $[\text{Cu}]$ fragment to reveal low concentrations of the reactive terminal species $[\text{Cu}]=\text{NR}$. Importantly, this strategy also allows for the isolation of dicopper nitrenes for which the terminal species may be inherently unstable as we found for 1° and 2° species **5** and **6**. This approach has also been applied to the isolation of cationic N -tosylnitrene complexes which has an additional $\kappa^2\text{-N,O}$ bonding mode accessible. For instance, Vedernikov and Caulton first described a purple complex of formulation $\{[\text{LCu}]_2(\text{NTs})\}^{2+}$ upon reaction of $\text{PhI}=\text{NTs}$ and their copper(I) catalyst.^{14,24} In a related chelating amine framework, formal substitution of a $[\text{LCu}]^+$ fragment for ScOTf_3 resulted in $[\text{N}_3]\text{Cu}(\mu\text{-NTs})\text{-ScOTf}_3$, a formulation supported by spectroscopy and theory (Figure 1).²¹

Our studies of C–H amination that proceed through the terminal copper alkylnitrene $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NR}$ clearly reveal that C–H amination takes place via a stepwise HAA/RR mechanism. A joint experimental/theory report by Nicholas, Houk, and colleagues that examined putative cationic $\{(\text{diimine})\text{Cu}(\text{NTs})\}^+$ intermediates provided evidence for competing direct insertion and HAA/RR pathways. For

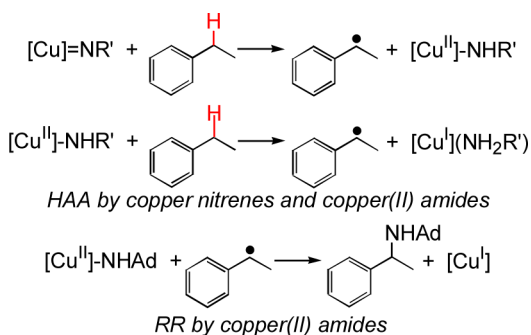
instance, reaction of a catalyst mixture prepared from the diimine ligand in Figure 2 and $[\text{Cu}(\text{NCMe})_4]\text{PF}_6$ (10 mol %) with $\text{PhI}=\text{NTs}$ in the presence of radical clock substrate **4** gave an 18% and 6% yield of the ring opened and ring closed C–H amination products.²⁰

Previous studies with the closely related $[\text{Cl}_2\text{NN}]\text{Cu}/\text{N}_3\text{Ad}$ catalytic system revealed a linear correlation between the $\ln(\text{rate})$ of C–H amination of substrates R–H and the C–H bond strength.¹⁵ Normalizing for the number of equivalent reacting C–H bonds, a C–H bond in cyclohexane (C–H BDE = 97 kcal/mol) reacts 480 times slower than a C–H bond in Indane (C–H BDE = 85 kcal/mol) at 110 °C. A rate limiting HAA process was also suggested for Ray's recently reported Lewis acid stabilized tosylnitrene due to the linear correlation of $\ln(\text{rate})$ versus C–H bond strength.²¹ Furthermore, kinetic isotope measurements reveal similar KIEs for copper nitrene intermediates that engage in HAA reactions. The $[\text{Cl}_2\text{NN}]\text{Cu}/\text{N}_3\text{Ad}$ system gave KIEs of 5.3(2) and 6.6(1) for the C–H amination of ethylbenzene and cyclohexane at 110 °C, respectively.¹⁵ Importantly, stoichiometric C–H amination of ethylbenzene with $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-NAd})$ gave an identical KIE of 5.1(2) under related conditions. Nicholas observed a KIE of 4.6 in the C–H amination of cumene by the $\{(\text{diimine})\text{Cu}\}^+/\text{PhI}=\text{NTs}$ system at RT²⁰ while Ray reported a KIE of 5.1 in the HAA of dihydroanthracene at –90 °C. KIEs in the range of 4–12 have been reported for species such as (porph)Ru(=NTs)₂ suggested^{5,6} and $[\text{Me}_3\text{NN}]\text{Ni}=\text{NAd}$ demonstrated²⁵ to participate in HAA reactions, though higher KIEs that deviate significantly from the value for classical H-atom transfer (6.5)²⁶ have been observed via Fe(III)-imide intermediates by Betley (13–24).⁹

Clear evidence for a HAA/RR pathway for reaction of $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NR}'$ with R–H indicates that $[\text{Cl}_2\text{NN}]\text{Cu-NHR}'$ species serve as intermediates in C–H amination. Previously, we have shown that 2 equiv of $[\text{Cl}_2\text{NN}]\text{Cu-NHAd}$ engage in stoichiometric C–H amination of ethylbenzene by a HAA/RR sequence.²² Thus, it is of interest to compare the intrinsic HAA reactivity of the terminal copper nitrene $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NR}'$ and copper(II) amide $[\text{Cl}_2\text{NN}]\text{Cu-NHR}'$ ($\text{R}' = \text{Ad}, \text{'Bu}$) species. A rate constant of $2.2(2) \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1}$ at 25 °C could be measured for HAA of ethylbenzene by $[\text{Cl}_2\text{NN}]\text{Cu-NHAd}$ (Scheme 7).²²

While we are unfortunately unable to directly compare the C–H bond reactivity of $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NR}'$ ($\text{R}' = \text{Ad}$ or 'Bu) species, it is clear that it is much higher. Analysis of the experimental data and the rate law derived from steady state analysis (Scheme 4a and Supporting Information Table S3)

Scheme 7. Roles for $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NR}'$ and $[\text{Cl}_2\text{NN}]\text{Cu-NHR}'$ in C–H Amination



suggests the relationship $k_{\text{HAA}} \approx 6 \times 10^{-6}/K_{\text{eq}}$. While we do not have an experimental value for K_{eq} corresponding to dissociation of $[\text{Cl}_2\text{NN}]\text{Cu}$ from $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-N}^t\text{Bu})$ (**3**) in benzene (Scheme 4a, eq 1), K_{eq} is lower than 10^{-2} based on NMR analysis. No new nitrene species could be seen in the RT NMR spectrum of **3** in benzene-*d*₆. Based on calculations that accompanied the initial report of **1**,^{15,27} dissociation of a $[\text{Cu}^1]$ fragment from **1** as $[\text{Cl}_2\text{NN}]\text{Cu}(\text{benzene})$ corresponds to $\Delta G = +5.8$ kcal/mol at 298 K. Taking into account the concentration of neat benzene, an equilibrium constant $K_{\text{eq}} \approx 1 \times 10^{-3}$ may be crudely estimated at 40 °C. Using this estimate of K_{eq} for dissociation of $[\text{Cu}^1]$ from $[\text{Cu}]_2(\mu\text{-N}^t\text{Bu})$, we find that HAA of ethylbenzene by $[\text{Cl}_2\text{NN}]\text{Cu}=\text{N}^t\text{Bu}$ should possess a bimolecular rate constant in the vicinity of ca. $6 \times 10^{-3} \text{ M}^{-1} \text{ s}^{-1}$ at 40 °C.

These data speak to the very high HAA reactivity of the terminal nitrene species $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NR}'$ ($\text{R}' = \text{Ad}, \text{'Bu}$) species which is at least 2 orders of magnitude greater than that of $[\text{Cl}_2\text{NN}]\text{Cu-NHAd}$ ²² and the closely related nickel-imide $[\text{Me}_3\text{NN}]\text{Ni}=\text{NAd}$ ($k_{\text{HAA}} = 2.4(2) \times 10^{-5} \text{ M}^{-1} \text{ s}^{-1}$ for ethylbenzene at 35 °C).²⁵ The origin of the high reactivity of terminal alkylnitrene species $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NR}$ is the high N–H bond strength in the copper(II) amide $[\text{Cl}_2\text{NN}]\text{Cu-NHR}'$ calculated to be 98.4 kcal/mol for $[\text{Cl}_2\text{NN}]\text{Cu-NHAd}$.²⁵ In comparison, the N–H BDEs in $[\text{Cl}_2\text{NN}]\text{Cu}(\text{NH}_2\text{Ad})$ and $[\text{Me}_3\text{NN}]\text{Ni-NHAd}$ are calculated to be 68 and 85.2 kcal/mol, respectively.^{22,25}

Unfortunately, the high reactivity of terminal copper nitrene species also facilitates rapid α -H migration reactions via $[\text{Cl}_2\text{NN}]\text{Cu}=\text{NHRR}'$ intermediates to give imine adducts $[\text{Cl}_2\text{NN}]\text{Cu}(\text{HN}=\text{NRR}')$. Such rearrangements in copper-alkylnitrene complexes are reminiscent of α -H migration processes observed in free singlet alkylnitrenes.^{28,29} For instance, photolysis of the alkyl azide CH_3N_3 results in formation of $\text{HN}=\text{CH}_2$ via singlet $[\text{CH}_3\text{N}]$.²⁸ A related α -H migration takes place from an Ir(III) benzylazide complex $[\text{Ir}](\text{N}_3\text{CH}_2\text{Ph})$ with loss of N_2 to give the corresponding $[\text{Ir}](\text{NH}=\text{CHPh})$ species, but no Ir-nitrene intermediate was observed.³⁰ Although this α -H migration limits the use of 1° and 2° alkylazides for catalytic C–H amination with the $[\text{Cl}_2\text{NN}]\text{Cu}$ catalyst, we recently reported an alternative protocol with this catalyst that employs unactivated alkylamines such as H_2NCy and $\text{H}_2\text{NCH}_2\text{CH}_2\text{Ph}$ with $\text{'BuOO}^t\text{Bu}$ as oxidant.²²

The β -diketiminato copper nitrenes $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-NR}')$ ($\text{R}' = \text{Ad}, \text{'Bu}$) represent sparse members of isolated and/or well characterized late first row transition metal imides/nitrenes that show high reactivity toward C–H amination of strong sp^3 C–H bonds. Zhang provided EPR evidence supporting the presence of porphyrin Co(III)-nitrene radical intermediates capable of HAA/RR with 2° benzylic C–H substrates.¹¹ A high spin dipyrromethene Fe^{III}-imido $[\text{Fe}]=\text{NAr}'$ ($\text{Ar}' = 4\text{'BuC}_6\text{H}_4$) isolated by Betley and co-workers directly aminates toluene.⁹ We recently reported that the β -diketiminato nickel(III) imide $[\text{Me}_3\text{NN}]\text{Ni}=\text{NAd}$ undergoes HAA with benzylic R–H substrates indane, ethylbenzene, and toluene to form the nickel-amide $[\text{Me}_3\text{NN}]\text{Ni-NHAd}$ and hydrocarbyl radical R^\bullet . Attack of the nickel-imide by R^\bullet led to formation of the nickel(II) amides $[\text{Me}_3\text{NN}]\text{Ni-N}(\text{R})\text{Ad}$, though the C–H amination product $\text{HN}(\text{R})\text{Ad}$ is observed in the reaction of $[\text{Me}_3\text{NN}]\text{Ni}=\text{NAd}$ with indane.²⁵ Hillhouse et al. has isolated a low-coordinate nickel imido complex with an especially bulky NHC ligand, $(\text{IPr}^*)\text{Ni}=\text{N}(\text{dmp})$ ($\text{dmp} = 2,6\text{-dimesitylphen-}$

yl).³¹ This nickel imido complex reacts with ethene, forming the vinylamine (dmp)NH(CH=CH₂).

Since the rate of C–H amination via HAA/RR is strongly coupled to the loss of a [Cu^I] fragment from dicopper nitrenes [Cu]₂(μ-NR'), synthetic studies that focus on the use of especially bulky β-diketiminato ligands and/or nitrene substituents that discourage the formation of dinuclear species should be expected to yield a significant rate enhancement. Coupled with the calculated strength of the N–H bond in [Cl₂NN]Cu–NHAd (98.4 kcal/mol) formed via HAA of a substrate R–H via terminal [Cl₂NN]Cu=NAd,²⁵ such approaches may place the catalytic functionalization of methane (C–H BDE = 105 kcal/mol)³² via β-diketiminato [Cu]=NR' species within reach.³³

EXPERIMENTAL SECTION

General Procedures. All experiments were carried out in a dry nitrogen atmosphere using an MBraun glovebox and/or standard Schlenk techniques, unless otherwise stated. 4A molecular sieves were activated in vacuo at 180 °C for 24 h. Dry benzene and dichloromethane were purchased from Aldrich and were stored over activated 4A molecular sieves under nitrogen. Diethyl ether and tetrahydrofuran (THF) were first sparged with nitrogen and then dried by passage through activated alumina columns. Pentane was first washed with conc. HNO₃/H₂SO₄ to remove olefins, stored over CaCl₂, and then passed through activated alumina columns. All deuterated solvents were sparged with nitrogen, dried over activated 4A molecular sieves, and stored under nitrogen. ¹H and ¹³C NMR spectra were recorded on a Varian 400 MHz spectrometer (400 and 100.4 MHz, respectively). All NMR spectra were recorded at room temperature unless otherwise noted and were indirectly referenced to TMS using residual solvent signals as internal standards. GC-MS spectra were recorded on a Varian Saturn 2100T, elemental analyses were performed on a Perkin-Elmer PE2400 microanalyzer in our laboratories, and UV–vis spectra were recorded on a Cary 50 spectrophotometer.

All reagents were obtained commercially unless otherwise noted and typically stored over activated 4A molecular sieves. Ethylbenzene was obtained from Acros and purified by passing each through activated alumina. {[Cl₂NN]Cu}₂(μ-benzene) (**2**) was prepared by literature methods¹⁵ or may be obtained from Strem Chemicals (#29-7050). *cis*- and *trans*-1,4-Dimethylcyclohexane were obtained from TCI America and purified by passing each through activated alumina. Following literature procedures, N₃^tBu³⁴ and N₃Cy³⁵ were prepared by reaction of NaN₃ with either ^tBuOH or CyBr under appropriate conditions. N₃CH₂CH₂Ph was prepared via modification of published procedures involving tosylation of PhCH₂CH₂OH³⁶ followed by reaction of PhCH₂CH₂OTs with NaN₃.³⁷ **Caution!** While some organoazides can explosively decompose upon heating, exposure to high fluxes of light, or exposure to some metal complexes and some metal surfaces, we did not experience any such uncontrolled reactivity in this work. All catalytic reactions with azides at elevated temperatures were performed in pressure vessels behind a Plexiglas shield.

Preparation of Compounds. {[Cl₂NN]Cu}₂(μ-N^tBu) (**3**). To slurry of {[Cl₂NN]Cu}₂(benzene) (0.173 g, 0.177 mmol) in 30 mL of pentane was added a solution of N₃^tBu (0.143 g, 1.44 mmol) in 20 mL of pentane. This yellowish suspension was stirred for 24 h at RT; after ~10 min, it turned into a yellow-green slurry. The mixture was passed through a short Celite stick (ca. 1 cm³), and the solvent was immediately removed in vacuo. The dark green residue was taken into ~10 mL pentane, filtered through a short Celite stick (ca. 1 cm³), concentrated in vacuo to ~3 mL, and allowed to stand overnight at –35 °C. Dark green blocks of the product formed (0.079 g, 46%) that were suitable for X-ray diffraction. ¹H NMR (400 MHz, benzene-*d*₆, RT): δ 6.99 (d, 8, *Ar-m-H*), 6.42 (t, 4, *Ar-p-H*), 5.15 (s, 2, backbone –CH), 1.64 (s, 12, backbone –CH₃), 0.75 (s, 9, ^tBu –CH₃). ¹³C{¹H} NMR (100 MHz, benzene-*d*₆): δ 164.85, 147.31, 128.51, 128.27, 125.70, 100.11, 73.96, 29.95, 23.43. UV–vis: λ_{max} (benzene) = 714 nm

(3960 cm^{–1} M^{–1}) with other prominent optical bands centered at 459 and 598 nm (Supporting Information Figure S1). Anal. Calcd. For C₃₈H₃₅Cl₈N₅Cu₂: C, 46.93; H, 3.63; N, 7.20. Found: C, 47.33; H, 3.86; N, 6.69.

{[Cl₂NN]Cu}₂(μ-NCH₂CH₂Ph) (**5**). N₃CH₂CH₂Ph (0.050 g, 0.340 mmol) in 2 mL of chlorobenzene was added to a stirring solution {[Cl₂NN]Cu}₂(benzene) (0.060 g, 0.060 mmol) in 5 mL of chlorobenzene. The initially yellow color of the solution turned dark blue/purple in 2 min with effervescence of N_{2(g)}. The solution was stirred for only 10 min at room temperature, and the solvent was immediately removed in vacuo. The resulting purple residue was dissolved in cold pentane (3 mL) and then filtered through a short Celite stick (ca. 1 cm³) and allowed to stand overnight at –35 °C. Dark blue/purple crystals formed from the solution to afford 0.040 g (66%) of the product suitable for X-ray diffraction. Room temperature benzene-*d*₆ solutions of this compound convert quickly (<10 min) to [Cl₂NN]Cu(NH=CHCH₂Ph) (**7**) and [Cl₂NN]Cu(benzene)¹⁵ as monitored by ¹H NMR.

{[Cl₂NN]Cu}₂(μ-NCy) (**6**). N₃Cy (0.170 g, 1.36 mmol) in 5 mL of pentane was added to a stirring slurry of {[Cl₂NN]Cu}₂(benzene) (0.259 g, 0.264 mmol) in 10 mL of pentane. The initially yellow color of the slurry turned greenish blue in 2 min with effervescence of N_{2(g)}. The mixture was stirred for 10 min at room temperature and immediately filtered through a short Celite stick (ca. 1 cm³), and the solvent was removed in vacuo. The resulting dark blue-green residue was extracted with cold pentane (~1.5 mL, –35 °C), passed through a short Celite stick (ca. 1 cm³), and allowed to stand overnight at –35 °C. Dark blue crystals formed that were suitable for X-ray diffraction. Room temperature benzene-*d*₆ solutions of this compound convert quickly (<5 min) to [Cl₂NN]Cu(NH=*c*-C₆H₁₀) (**7**) and [Cl₂NN]Cu(benzene)¹⁵ as monitored by ¹H NMR spectroscopy, undergoing α-H migration qualitatively faster than **5**.

[Cl₂NN]Cu(NH=CHCH₂Ph) (**7**). N₃CH₂CH₂Ph (0.030 g, 0.204 mmol) in 3 mL of ether was added to a stirring solution {[Cl₂NN]Cu}₂(benzene) (0.100 g, 0.103 mmol) in 7 mL of ether. The initial yellow color of the solution turned dark blue/purple in 2 min with effervescence of N_{2(g)} and left to stir for 1 h at RT upon which the solution turned back to the initial yellow color. The solution was filtered through Celite and concentrated in vacuo to ca. 2 mL and allowed to stand overnight at –35 °C. Pale yellow crystals crashed out of solution that were collected and dried to afford 0.090 g (78%) of crystals that were suitable for X-ray diffraction. ¹H NMR (400 MHz, benzene-*d*₆): δ 7.71 (d, 1, NH imine), 7.08 (d, 4, *Ar-m-H*), 7.03 (d, 2, Ph), 6.96 (t, 1, Ph), 6.67 (dd, 1, Ph), 6.37 (t, 2, *Ar-p-H*), 6.20 (dt, 1, HN=CHCH₂), 5.03 (s, 1, backbone-CH), 3.18 (d, 2, HN=CHCH₂), 1.86 (s, 6, backbone CH₃). ¹³C{¹H} NMR (100 MHz, benzene-*d*₆): δ 171.76 (=CH imine), 164.1, 148.94, 134.84, 130.59, 129.60, 29.36, 129.21, 128.58, 127.47, 123.16, 95.41, 45.50, 23.52. IR, thin film: 3283 cm^{–1} (N–H). Anal. Calcd. For C₂₅H₂₂Cl₄N₃Cu: C, 52.70; H, 3.89; N, 7.37. Found: C, 52.57; H, 3.66; N, 7.07.

[Cl₂NN]Cu(NH=C₆H₁₀) (**8**). N₃Cy (0.166 g, 1.33 mmol) in 5 mL of ether was added to a stirring slurry of {[Cl₂NN]Cu}₂(benzene) (0.245 g, 0.205 mmol) in 10 mL of ether. The color of the mixture turned greenish blue in 2 min with effervescence of N_{2(g)}. The mixture was left to stir for 24 h at RT upon which its color turned back to the initial yellow color. The mixture was filtered through Celite and concentrated in vacuo to ca. 2 mL and allowed to stand overnight at –35 °C. Yellow crystals that crashed out of solution were collected and dried to afford 0.135 g (49%) that was suitable for X-ray diffraction. ¹H NMR (400 MHz, benzene-*d*₆): δ 7.38 (s, 1, NH imine), 7.10 (d, 4, *Ar-m-H*), 6.37 (t, 2, *Ar-p-H*), 5.03 (s, 1, backbone-CH), 2.02 (t, 2, α-CH₂ from =C), 1.88 (s, 6, backbone-CH₃), 1.14 (d, 2, β-CH₂ from =C), 0.99 (t, 2, α-CH₂ from =C), 0.87 (q, 2, γ-CH₂ from =C), 0.81 (d, 2, β-CH₂ from =C). ¹³C{¹H} NMR (100 MHz, benzene-*d*₆): δ 183.42 (=CH imine), 163.80, 149.03, 130.61, 128.50, 122.85, 95.21, 39.41, 38.84, 27.14, 26.91, 25.06, 23.57. IR, thin film: 3276 cm^{–1} (N–H). Anal. Calcd. For C₂₃H₂₄Cl₄N₃Cu: C, 50.43; H, 4.42; N, 7.67. Found: C, 50.65; H, 4.43; N, 7.40.

Kinetic Measurement by UV–Vis Spectroscopy. Solutions for kinetic analysis by UV–vis spectroscopy were prepared using freshly

prepared and crystallized **3**. A known amount of **3** was dissolved in RT benzene to a known volume using a volumetric flask. This sample was used for UV-vis analysis and stored frozen at $-35\text{ }^{\circ}\text{C}$ until needed. A known portion of this stock solution (unfrozen) was added with appropriate amounts of ethylbenzene and $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\text{benzene})$, followed by dilution to 10.0 mL with benzene at RT. The decreasing concentration of **3** at $40.0\text{ }^{\circ}\text{C}$ was quantified by UV-vis spectroscopy employing an 18 s scan interval, by considering the decrease in absorbance at $\lambda_{\text{max}} = 714\text{ nm}$. The method of initial rates was used for kinetic analyses to minimize the effect of $[\text{Cl}_2\text{NN}]\text{Cu}$ generation in C-H amination by $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\mu\text{-N}^t\text{Bu})$ which leads to a deceleration of effective rates. Details of these kinetic analyses may be found in the Supporting Information.

Catalytic Amination of *cis*- and *trans*-1,4-Dimethylcyclohexane with N_3^tBu . Two portions of N_3^tBu (0.198 g, 2.00 mmol) were dosed, one mixed with *cis*-1,4-dimethylcyclohexane (6.00 mL, 41.8 mmol) and the other with the *trans*-isomer (6.00 mL, 40.6 mmol). A solution of $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\text{benzene})$ (1.00 mL, 0.025 M, 0.025 mmol, 2.5 mol % relative to $\text{N}_3^t\text{Bu} = 5\text{ mol } \% [\text{Cu}]$ relative to N_3^tBu) in benzene was added into each of the aliquot of the azide-substrate solution (3.00 mL). These reaction mixtures were heated for 48 h at $100\text{ }^{\circ}\text{C}$ in a sealed, thick walled reaction vessel. The color of the solution changed from light yellow to dark green. The mixtures were quenched by exposing to air for several hours, filtered through Celite stick, and analyzed via GC/MS in CH_2Cl_2 . GC/MS indicated that there are no other products except for the aminated products. The solvent was removed in vacuo from each reaction mixture, the residue was taken as the crude yield for the reaction, 55% (0.105 g) for the *cis*-isomer, and 50% (0.0915 g) for the *trans*-isomer. Amination at both tertiary and secondary C-H bonds was observed, with selectivity of $3^{\circ}:2^{\circ} = 75:25$ and $25:75$ for *cis*- and *trans*-isomer, respectively. Tertiary products were obtained in the same distribution (44:56 for *trans*-isomer and 46:64 for *cis*-isomer), irrespective of substrate used. Detailed analysis of the product distribution from the catalytic amination of these substrates is found in the Supporting Information.

Catalytic Amination of a Benzylic Radical Clock. The substrate 1-benzyl-*trans*-2-phenylcyclopropane (**4**) was prepared following a modified cyclopropanation procedure of *trans*-1,3-diphenylpropene²³ with trifluoroacetic acid, diethylzinc, and diiodomethane.³⁸ Detailed synthetic procedures are provided in the Supporting Information.

A solution of 1-benzyl-*trans*-2-phenylcyclopropane (0.150 g, 0.720 mmol) and N_3^tBu (0.357 g, 3.60 mmol) was added into a slurry of $\{[\text{Cl}_2\text{NN}]\text{Cu}\}_2(\text{benzene})$ (0.353 g, 0.360 mmol) in benzene (1.00 mL). The reaction was allowed to stir at $100\text{ }^{\circ}\text{C}$ for 48 h in a sealed, thick walled reaction vessel. The color changed to dark green after only 2 min and then to dark brown toward the end of the reaction. After quenching the reaction by exposing it to air for several hours, the solution was filtered through Celite and the solvent was removed under vacuum. GC/MS analysis of the crude reaction mixture revealed only one C-H amination product of the radical clock ($m/z = 280$) along with unreacted radical clock and a small amount of a product from the amination of the reactive *trans*-1,3-diphenylpropene impurity. The crude mixture was chromatographed on silica using 8:2 CH_2Cl_2 /methanol as eluents. The third pooled fraction was collected and contained the aminated radical clock. The solvent was removed in vacuo, resulting in a dark brown oily residue in 80% (0.160 g) yield. Precipitating the product amine with ethereal HCl resulted in an HCl salt whose ^1H NMR analysis is consistent with a ring-opened aminated product. ^1H NMR of the HCl salt (400 MHz, chloroform- d_1): δ 9.63 (m, 2, $-\text{NH}\cdot\text{HCl}$), 7.72 (m, Ar-H), 7.40 (m, Ar-H), 7.34 (m, Ar-H), 7.14 (m, Ar-H), 7.07 (m, Ar-H), 6.59 (m, Ar-H), 6.32 (d, 1, vinylic H, J_{HH} Hz = 16), 5.65 (m, 1, vinylic H, J_{HH} Hz = 16), 4.27 (m, 1, benzylic $-\text{CH}$), 3.83 (m, 1, $-\text{CH}_2$), 3.20 (m, 1, $-\text{CH}_2$), 1.36 (s, 9, $-\text{Bu}$ CH_3) (see Figure S8 in the Supporting Information for labeling and $^1\text{H}-^1\text{H}$ correlation spectrum).

■ ASSOCIATED CONTENT

■ Supporting Information

Additional synthetic, characterization, and kinetics details, along with X-ray details including fully labeled thermal ellipsoid plots for compounds **3** and **5–8** (also provided in .cif format). This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

thw@georgetown.edu.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We are grateful to NSF (CHE-1012523) for financial support of this work. We appreciate many insightful conversations with Prof. Tom Cundari of the University of North Texas. We also thank Dr. Roland Fröhlich of the University of Münster, Germany, for assistance with the refinement of the X-ray structure of **3**.

■ REFERENCES

- (1) (a) Dauban, P.; Dodd, R. H. In *Amino Group Chemistry*; Ricci, A., Ed.; Wiley-VCH: Weinheim, 2008; pp 55–92. (b) Collet, F.; Dodd, R. H.; Dauban, P. *Chem. Commun.* **2009**, 5061–5074. (c) Collet, F.; Lescot, C.; Liang, C.; Dauban, P. *Dalton Trans.* **2010**, 39, 10401–10413. (d) Zalatan, D. N.; Du Bois, J. *Top. Curr. Chem.* **2010**, 292, 347–378. (e) Zhang, X. P.; Lu, H. *Chem. Soc. Rev.* **2011**, 40, 1899–1909.
- (2) Berry, J. F. *Comments Inorg. Chem.* **2009**, 30, 28–66.
- (3) Fiori, K. W.; Du Bois, J. *J. Am. Chem. Soc.* **2007**, 129, 562–568.
- (4) (a) Liang, C.; Collet, F.; Robert-Peillard, F.; Muller, P.; Dodd, R. H.; Dauban, P. *J. Am. Chem. Soc.* **2008**, 130, 343–350. (b) Du Bois, J. *Org. Process Res. Dev.* **2011**, 15, 758–762. (c) Huard, K.; Lebel, H. *Chem.—Eur. J.* **2008**, 14, 6222–6230. (d) Lebel, H.; Huard, K.; Lectard, S. *J. Am. Chem. Soc.* **2005**, 127, 14198–14199.
- (5) (a) Au, S.-M.; Huang, J.-S.; Yu, W.-Y.; Fung, W.-H.; Che, C.-M. *J. Am. Chem. Soc.* **1999**, 121, 9120–9132. (b) Leung, S. K.-Y.; Tsui, W.-M.; Huang, J.-S.; Che, C.-M.; Liang, J.-L.; Zhu, N. *J. Am. Chem. Soc.* **2005**, 127, 16629–16640.
- (6) Au, S.-M.; Huang, J.-S.; Che, C.-M.; Yu, W.-Y. *J. Org. Chem.* **2000**, 65, 7858–7864.
- (7) (a) Harvey, M. E.; Musaev, D. G.; Du Bois, J. *J. Am. Chem. Soc.* **2011**, 133, 17207–17216. (b) Liang, J.-L.; Yuan, S.-X.; Huang, J.-S.; Yu, W.-Y.; Che, C.-M. *Angew. Chem., Int. Ed.* **2002**, 41, 3465–3468. (c) Milczek, E.; Boudet, N.; Blakey, S. *Angew. Chem., Int. Ed.* **2008**, 47, 6825–6828. (d) Yu, X.-Q.; Huang, J.-S.; Zhou, X.-G.; Che, C.-M. *Org. Lett.* **2000**, 2, 2233–2236.
- (8) Zhang, J.; Chan, P. W. H.; Che, C.-M. *Tetrahedron Lett.* **2005**, 46, 5403–5408.
- (9) King, E. R.; Hennessy, E. T.; Betley, T. A. *J. Am. Chem. Soc.* **2011**, 133, 4917–4923.
- (10) (a) Liu, Y.; Che, C.-M. *Chem.—Eur. J.* **2010**, 16, 10494–10501. (b) Wang, Z.; Zhang, Y.; Fu, H.; Jiang, Y.; Zhao, Y. *Org. Lett.* **2008**, 10, 1863–1866.
- (11) Lyaskovskyy, V.; Olivos Suarez, A. I.; Lu, H.; Jiang, H.; Zhang, X. P.; de Bruin, B. *J. Am. Chem. Soc.* **2011**, 133, 12264–12273.
- (12) (a) Caselli, A.; Gallo, E.; Fantauzzi, S.; Morlacchi, S.; Ragaini, F.; Cenini, S. *Eur. J. Inorg. Chem.* **2008**, 3009–3019. (b) Cenini, S.; Gallo, E.; Penoni, A.; Ragaini, F.; Tollari, S. *Chem. Commun.* **2000**, 2265–2266. (c) Lu, H.; Subbarayan, V.; Tao, J.; Zhang, X. P. *Organometallics* **2010**, 29, 389–393. (d) Lu, H.; Tao, J.; Jones, J. E.; Wojitas, L.; Zhang, X. P. *Org. Lett.* **2010**, 12, 1248–1251. (e) Ruppel, J. V.; Kamble, R. M.; Zhang, X. P. *Org. Lett.* **2007**, 9, 4889–4892.

- (13) (a) Díaz-Requejo, M. M.; Belderrain, T. R.; Nicasio, M. C.; Trofimenko, S.; Pérez, P. J. *J. Am. Chem. Soc.* **2003**, *125*, 12078–12079. (b) Fructos, M. R.; Trofimenko, S.; Díaz-Requejo, M. M.; Pérez, P. J. *J. Am. Chem. Soc.* **2006**, *128*, 11784–11791. (c) Hamilton, C. W.; Laitar, D. S.; Sadighi, J. P. *Chem. Commun.* **2004**, 1628–1629. (d) Liu, X.; Zhang, Y.; Wang, L.; Fu, H.; Jiang, Y.; Zhao, Y. *J. Org. Chem.* **2008**, *73*, 6207–6212.
- (14) Vedernikov, A. N.; Caulton, K. G. *Chem. Commun.* **2004**, 162–163.
- (15) Badiei, Y. M.; Dinescu, A.; Dai, X.; Palomino, R. M.; Heinemann, F. W.; Cundari, T. R.; Warren, T. H. *Angew. Chem., Int. Ed.* **2008**, *47*, 9961–9964.
- (16) Gephart, R. T., III; Warren, T. H. *Organometallics* **2012**, *31*, 7728–7752.
- (17) Fantauzzi, S.; Gallo, E.; Caselli, A.; Ragaini, F.; Casati, N.; Macchi, P.; Cenini, S. *Chem. Commun.* **2009**, 3952–3954.
- (18) Badiei, Y. M.; Krishnaswamy, A.; Melzer, M. M.; Warren, T. H. *J. Am. Chem. Soc.* **2006**, *128*, 15056–15057.
- (19) Kwart, H.; Khan, A. A. *J. Am. Chem. Soc.* **1967**, *89*, 1951–1953.
- (20) Barman, D. N.; Liu, P.; Houk, K. N.; Nicholas, K. M. *Organometallics* **2010**, *29*, 3404–3412.
- (21) Kundu, S.; Miceli, E.; Farquhar, E.; Pffaff, F. F.; Kuhlmann, U.; Hildebrandt, P.; Braun, B.; Greco, C.; Ray, K. *J. Am. Chem. Soc.* **2012**, *134*, 14710–14713.
- (22) Wiese, S.; Badiei, Y. M.; Gephart, R. T.; Mossin, S.; Varonka, M. S.; Melzer, M. M.; Meyer, K.; Cundari, T. R.; Warren, T. H. *Angew. Chem., Int. Ed.* **2010**, *49*, 8850–8855.
- (23) Hollis, R.; Hughes, L.; Bowry, V. W.; Ingold, K. U. *J. Org. Chem.* **1992**, *57*, 4284–4287.
- (24) Vedernikov, A. N.; Caulton, K. G. *Org. Lett.* **2003**, *5*, 2591–2594.
- (25) Wiese, S.; McAfee, J. L.; Pahls, D. R.; McMullin, C. L.; Cundari, T. R.; Warren, T. H. *J. Am. Chem. Soc.* **2012**, *134*, 10114–10121.
- (26) Anslyn, E. V.; Dougherty, D. A. In *Modern Physical Organic Chemistry*; University Science Books: Sausalito, CA, 2006.
- (27) Cundari, T. R. Personal communication.
- (28) Platz, M. S. In *Reactive Intermediate Chemistry*; Moss, R. A., Platz, M. S., Jones, M. J., Eds.; John Wiley and Sons: Hoboken, NJ, 2004; pp 501–559.
- (29) Horner, L.; Christmann, A. *Angew. Chem., Int. Ed.* **1963**, *2*, 599–608.
- (30) Albertin, G.; Antoniutti, S.; Baldan, D.; Castro, J.; Garcia-Fontán, S. *Inorg. Chem.* **2008**, *47*, 742–748.
- (31) Laskowski, C. A.; Miller, A. J. M.; Hillhouse, G. L.; Cundari, T. R. *J. Am. Chem. Soc.* **2011**, *133*, 771–773.
- (32) Luo, Y.-R. *Handbook of Bond Dissociation Energies in Organic Compounds*; CRC Press: Boca Raton, FL, 2002.
- (33) Tekarli, S. M.; Williams, T. G.; Cundari, T. R. *J. Chem. Theory Comput.* **2009**, *5*, 2959–2966.
- (34) Bottaro, J. C.; Penwell, P. E.; Schmitt, R. J. *Synth. Commun.* **1997**, *27*, 1465–1467.
- (35) Alvarez, S. G.; Alvarez, M. T. *Synthesis* **1997**, 413–414.
- (36) (a) Morita, J.; Nakatsuji, H.; Misaki, T.; Tanabe, Y. *Green Chem.* **2005**, *7*, 711–715. (b) Warren, T. H.; Erker, G.; Frohlich, R.; Wibbeling, B. *Organometallics* **2000**, *19*, 127–134.
- (37) DuBois, G. E.; Crosby, G. A.; McGarraugh, G. V.; Ng, S. Y.-W.; Stephenson, R. A.; Wang, P. A.; Wingard, J. R. E. *J. Org. Chem.* **1982**, *47*, 1319–1323.
- (38) Lorenz, J. C.; Long, J.; Yang, Z.; Xue, S.; Xie, Y.; Shi, Y. *J. Org. Chem.* **2004**, *69*, 327–334.